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Contributions of vector-like quarks to radiative B meson decay

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Abstract

We study the decay $B \to X_s\gamma$ in a minimal extension of the standard model with extra up- and down-type quarks whose left- and right-handed components are both SU(2) singlets. Constraints on the extended Cabibbo-Kobayashi-Maskawa matrix are obtained from the experimental results for the branching ratio. Even if the extra quarks are too heavy to be detected in near-future colliders, the branching ratio could have a value which is non-trivially different from the prediction of the standard model.

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The inclusive decay $B \to X_s\gamma$ is well described by the free quark decays $b \to s\gamma$ and $b \to s\gamma g$, owing to a large mass of the b quark. Since these decays are generated at the one-loop level of the electroweak interactions, the radiative B-meson decay is sensitive to new physics beyond the Standard Model (SM) [1], such as the supersymmetric model [2]. Its branching ratio could deviate from the prediction of the SM. Or some constraints could be imposed on new physics. Experimentally, the branching ratio has been measured by CLEO [3] and ALEPH [4] as

$$\mathrm{Br}(B \to X_s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}, \quad (1)$$

$$= (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}. \quad (2)$$

These results are consistent with the SM prediction $\mathrm{Br}(B \to X_s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$ [5], though still show room for the contribution of new physics.

The SM is minimally extended by incorporating extra colored fermions whose left-handed components, as well as right-handed ones, are singlets under the SU(2) gauge transformation, with electric charges being $2/3$ and/or $-1/3$. In this vector-like quark model (VQM), many features of the SM are not significantly modified. However, the interactions of the quarks with the W or Z boson are qualitatively different from those in the SM. The Cabibbo-Kobayashi-Maskawa (CKM) matrix for the charged current is extended and not unitary. The neutral current involves interactions between the quarks with different flavors. In addition, the neutral Higgs boson also mediates flavor-changing interactions at the tree level. The VQM could thus give sizable new contributions to processes of flavor-changing neutral current (FCNC) [6, 7] and of CP violation [8, 9].

In this paper we study the radiative B-meson decay within the framework of the VQM containing one up-type and one down-type extra quarks. The decay receives contributions from the interactions mediated by the W, Z, and Higgs bosons. The effects by the Z and Higgs bosons have already been studied and found to be small [7]. Our study is concentrated on the other effects coming from the W-mediated interactions. These interactions give contributions differently from the SM at the electroweak energy scale, since an extra up-type quark is involved and the CKM matrix is not the same as that of the SM. It will be shown that the decay width can be much different from the SM prediction, even if the extra quark is rather heavy. The experimental results for the decay rate thus impose non-trivial constraints on the extended CKM matrix.

We assume that there exist two extra Dirac fermions whose transformation properties are given by $(3, 1, 2/3)$ and $(3, 1, -1/3)$ for the SU(3)×SU(2)×U(1) gauge sym-

metry. The mass terms of the quarks are then expressed by 4×4 matrices. These mass matrices, which are denoted by M^u and M^d respectively for up- and down-type quarks, are diagonalized by unitary matrices A_L^u, A_R^u, A_L^d, and A_R^d as

$$\begin{aligned} A_L^{u\dagger} M^u A_R^u &= \mathrm{diag}(m_{u1}, m_{u2}, m_{u3}, m_{u4}), & (3)\\ A_L^{d\dagger} M^d A_R^d &= \mathrm{diag}(m_{d1}, m_{d2}, m_{d3}, m_{d4}). & (4)\end{aligned}$$

The mass eigenstates are expressed by u^a and d^a $(a = 1-4)$, a being the generation index, which are also called as (u, c, t, U) and (d, s, b, D).

The interaction Lagrangian for the quarks with the W and Goldstone bosons is given by

$$\begin{aligned} \mathcal{L} = & \frac{g}{\sqrt{2}} \sum_{a,b=1}^{4} \overline{u^a} V_{ab} \gamma^\mu \frac{1-\gamma_5}{2} d^b W_\mu^\dagger \\ & + \frac{g}{\sqrt{2}} \sum_{a,b=1}^{4} \overline{u^a} V_{ab} \left\{ \frac{m_{ua}}{M_W} \left(\frac{1-\gamma_5}{2} \right) - \frac{m_{db}}{M_W} \left(\frac{1+\gamma_5}{2} \right) \right\} d^b G^\dagger \\ & + \mathrm{h.c.}. \end{aligned} \tag{5}$$

Here the 4×4 matrix V stands for an extended Cabibbo-Kobayashi-Maskawa matrix, which is defined by

$$V_{ab} = \sum_{i=1}^{3} (A_L^{u\dagger})_{ai} (A_L^d)_{ib}. \tag{6}$$

It should be noted that V is not unitary:

$$(V^\dagger V)_{ab} = \delta_{ab} - A_{L4a}^{d*} A_{L4b}^d. \tag{7}$$

The interaction Lagrangian for the down-type quarks with the Z, Higgs, and Goldstone bosons is given by

$$\begin{aligned} \mathcal{L} = & -\frac{g}{\cos\theta_W} \sum_{a,b=1}^{4} \overline{d^a} \gamma^\mu \left\{ -\frac{1}{2} \left(V^\dagger V \right)_{ab} \frac{1-\gamma_5}{2} + \frac{1}{3} \sin^2\theta_W \delta_{ab} \right\} d^b Z_\mu \\ & -\frac{g}{2} \sum_{a,b=1}^{4} \overline{d^a} \left(V^\dagger V \right)_{ab} \left\{ \frac{m_{da}}{M_W} \left(\frac{1-\gamma_5}{2} \right) + \frac{m_{db}}{M_W} \left(\frac{1+\gamma_5}{2} \right) \right\} d^b H^0 \\ & + i\frac{g}{2} \sum_{a,b=1}^{4} \overline{d^a} \left(V^\dagger V \right)_{ab} \left\{ \frac{m_{da}}{M_W} \left(\frac{1-\gamma_5}{2} \right) - \frac{m_{db}}{M_W} \left(\frac{1+\gamma_5}{2} \right) \right\} d^b G^0. \end{aligned} \tag{8}$$

Since V is not a unitary matrix, there appear interactions of FCNC at the tree level. The Lagrangians in Eqs. (5) and (8) contain new sources of CP violation [8].

The decay $B \to X_s\gamma$ is approximated by the radiative b-quark decays, which are mediated by the W, Z, and Higgs bosons. The relevant effective Hamiltonian with five quarks is then written as

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} \left[\sum_{j=1}^{6} \left\{ C_j(\mu) O_j(\mu) + \widetilde{C}_j(\mu) \widetilde{O}_j(\mu) \right\} + \sum_{j=7}^{8} C_j(\mu) O_j(\mu) \right], \tag{9}$$

where O_j, $\widetilde{O}_j$ represent operators for the $\Delta B = 1$ transition, with C_j, $\widetilde{C}_j$ being their Wilson coefficients. The evaluated energy scale is denoted by μ. The four-quark operators induced by the gauge boson interactions are denoted by $O_j(j = 1-6)$ [10]. The Higgs boson interactions induce new four-quark operators, which are denoted by $\widetilde{O}_j(j = 1-6)$. The dipole operators for $b \to s\gamma$ and $b \to sg$ are denoted by O_7 and O_8, respectively, which are generated by the one-loop diagrams shown in Fig. 1. Hereafter, we only take the W boson interactions into consideration, since the contributions coming from the Z and Higgs boson interactions are known to be much smaller than the SM contribution.

At the leading order (LO), the Wilson coefficients C_2, C_7, and C_8 have non-vanishing values at $\mu = M_W$, which are given by

$$\begin{aligned}
C_2(M_W) &= V_{32}^* V_{33} + V_{42}^* V_{43} - (V^\dagger V)_{23}, && (10)\\
C_7(M_W) &= \frac{23}{36}(V^\dagger V)_{23} - \sum_{a=3}^{4} V_{a2}^* V_{a3} \frac{3}{2} r_a \left\{ \frac{2}{3} I_1(r_a) + J_1(r_a) \right\}, && (11)\\
C_8(M_W) &= \frac{1}{3}(V^\dagger V)_{23} - \sum_{a=3}^{4} V_{a2}^* V_{a3} \frac{3}{2} r_a I_1(r_a), && (12)\\
r_a &= \frac{m_{ua}^2}{M_W^2}.
\end{aligned}$$

The functions $I_1(r)$ and $J_1(r)$ are defined as [11]

$$\begin{aligned}
I_1(r) &= \frac{1}{12(1-r)^4}(2 + 3r - 6r^2 + r^3 + 6r \ln r), && (13)\\
J_1(r) &= \frac{1}{12(1-r)^4}(1 - 6r + 3r^2 + 2r^3 - 6r^2 \ln r). && (14)
\end{aligned}$$

The non-unitarity of the CKM matrix V yields the terms proportional to $(V^\dagger V)_{23}$ for C_2, C_7, and C_8. The Wilson coefficients at $\mu = m_b$ are obtained by solving the renormalization group equations. Using the LO anomalous dimension matrix, the coefficients are given by

$$C_2(m_b) = \frac{1}{2}(\eta^{-\frac{12}{23}} + \eta^{\frac{6}{23}}) C_2(M_W), \tag{15}$$

$$C_7(m_b) = \eta^{\frac{16}{23}} C_7(M_W) + \frac{8}{3}(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}) C_8(M_W) + \sum_{i=1}^{8} h_i \eta^{a_i} C_2(M_W), \quad (16)$$

$$C_8(m_b) = \eta^{\frac{14}{23}} C_8(M_W) + \sum_{i=1}^{8} \bar{h}_i \eta^{a_i} C_2(M_W), \quad (17)$$

with $\eta = \alpha_s(M_W)/\alpha_s(m_b)$ which is set for $\eta = 0.56$ in the following numerical study. The constants $h_i, \bar{h}_i$, and a_i are listed in Table 1 [12]. The branching ratio for $B \to X_s\gamma$ is obtained by normalizing the decay width to that of the semileptonic decay $B \to X_c e\overline{\nu}$, leading at the LO to

$$\mathrm{Br}(B \to X_s\gamma) = \frac{6\alpha_{\mathrm{EM}}}{\pi f(z)|V_{23}|^2} |C_7(m_b)|^2 \, \mathrm{Br}(B \to X_c e\overline{\nu}), \quad (18)$$

with $z = m_c^2/m_b^2$ and $f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z$.

The obtained branching ratio at the LO has non-negligible perturbative uncertainties, which are reduced by taking into account corrections at the next leading order (NLO). For the numerical evaluation, therefore, we incorporate NLO corrections for the matrix elements at $\mu = m_b$ [13] and the anomalous dimensions [14]. Our calculations follow formulae given in Ref. [5], which also include QED corrections.

The decay width of $B \to X_s\gamma$ depends on the U-quark mass m_U and the CKM matrix elements $V_{32}^* V_{33}$, $V_{42}^* V_{43}$, $(V^\dagger V)_{23}$. The value of $(V^\dagger V)_{23}$ determines the FCNC interactions at the tree level in Eq. (8), which is constrained from non-observation of $B \to K\mu^+\mu^-$ [15] as

$$|(V^\dagger V)_{23}| < 8.1 \times 10^{-4}. \quad (19)$$

The CKM matrix elements connecting light ordinary quarks, which are directly measured in experiments, have the same values as those in the SM. From the values of V_{12}, V_{13}, V_{22}, and V_{23} [15], we obtain a constraint

$$0.03 < |V_{32}^* V_{33} + V_{42}^* V_{43} - (V^\dagger V)_{23}| < 0.05. \quad (20)$$

The mass m_U should be heavier than the t-quark mass. In principle, the U-quark mass and the CKM matrix elements are not independent each other, their relations being determined by the mass matrices M^u and M^d. However, these relations depend on many unknown factors for the mass matrices. Furthermore, the values of m_U and $V_{42}^* V_{43}$ are thoroughly unknown phenomenologically except for the above constraints. We therefore take them for independent parameters.

The decay width is mainly determined by the Wilson coefficient $C_7(m_b)$ as seen from Eq. (18). Expressing explicitly the dependence on the CKM matrix elements,

the coefficient $C_7(m_b)$ in Eq. (16) is written as

$$C_7(m_b) = A_1(V^\dagger V)_{23} + A_2 V_{32}^* V_{33} + A_3 V_{42}^* V_{43}, \tag{21}$$

where A_3 is a function of m_U while A_1 and A_2 are constants. We show the m_U dependency of A_3 in Fig. 2, where A_1 and A_2 are also depicted. For $m_U \gtrsim 200$ GeV, the value of A_3 does not vary much with m_U and is comparable with A_2. Unless $V_{42}^* V_{43}$ is much smaller than $V_{32}^* V_{33}$, the coefficient $C_7(m_b)$ can be predicted differently from the SM value. Although A_1 is larger than A_2 and A_3 in magnitude, the smallness of $(V^\dagger V)_{23}$ makes the term $A_1(V^\dagger V)_{23}$ less important.

In Fig. 3 we show allowed regions for $V_{32}^* V_{33}$ and $V_{42}^* V_{43}$, assuming for simplicity that these values are real. The shaded regions are compatible with the experimental results of both Eq. (2) for $B \to X_s\gamma$ and Eq. (20) for the CKM matrix elements. The regions between the solid lines satisfy the latter. We have taken the U-quark mass for 200 GeV $< m_U <$ 1 TeV and $(V^\dagger V)_{23}$ for its maximal value 8.1×10^{-4}. The branching ratio of $B \to X_s\gamma$ sizably constrains the CKM matrix elements of the VQM. The allowed regions are slightly altered for $(V^\dagger V)_{23} = -8.1 \times 10^{-4}$.

In Fig. 4 the branching ratio of $B \to X_s\gamma$ is depicted as a function of m_U for $V_{42}^* V_{43} = -0.006, -0.002, 0.004, 0.006$. For definiteness, we put $V_{32}^* V_{33} = 0.04$ and $(V^\dagger V)_{23} = 8.1 \times 10^{-4}$. The experimental bounds Eqs. (1) and (2) are also shown. For $|V_{42}^* V_{43}/V_{32}^* V_{33}| \gtrsim 0.1$, the predicted value is non-trivially different from that of the SM. The branching ratio could have any value within the experimental bounds.

In summary, we have studied the effects of the VQM on the branching ratio for the radiative B-meson decay. Among the possible new contributions, the W-mediated diagrams yield sizable effects. From the experimental results for the branching ratio, the values of $V_{32}^* V_{33}$ and $V_{42}^* V_{43}$ are constrained. These constraints do not much depend on the mass of the extra quark U. The VQM could make the branching ratio of $B \to X_s\gamma$ different from the SM prediction. If precise measurements in the near future show a difference between the experimental value and the SM prediction, the VQM may become one candidate for physics beyond the SM.

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i	1	2	3	4	5	6	7	8
a_i	$\frac{14}{23}$	$\frac{16}{23}$	$\frac{6}{23}$	$-\frac{12}{23}$	0.4086	−0.4230	−0.8994	0.1456
h_i	$\frac{626126}{272277}$	$-\frac{56281}{51730}$	$-\frac{3}{7}$	$-\frac{1}{14}$	−0.6494	−0.0380	−0.0186	−0.0057
$\bar{h}_i$	$\frac{313063}{363036}$	0	0	0	−0.9135	0.0873	−0.0571	0.0209

Table 1: The values of h_i, $\bar{h}_i$, and a_i in Eqs. (16) and (17).

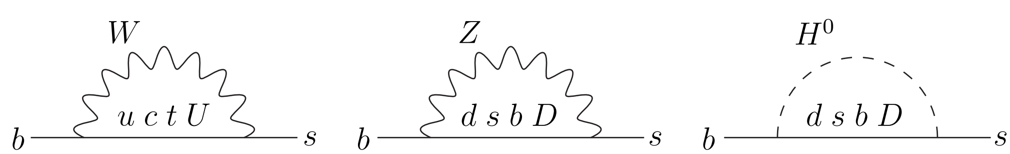

Figure 1: The diagrams which give contributions to C_7 and C_8. The photon or gluon line should be attached appropriately.

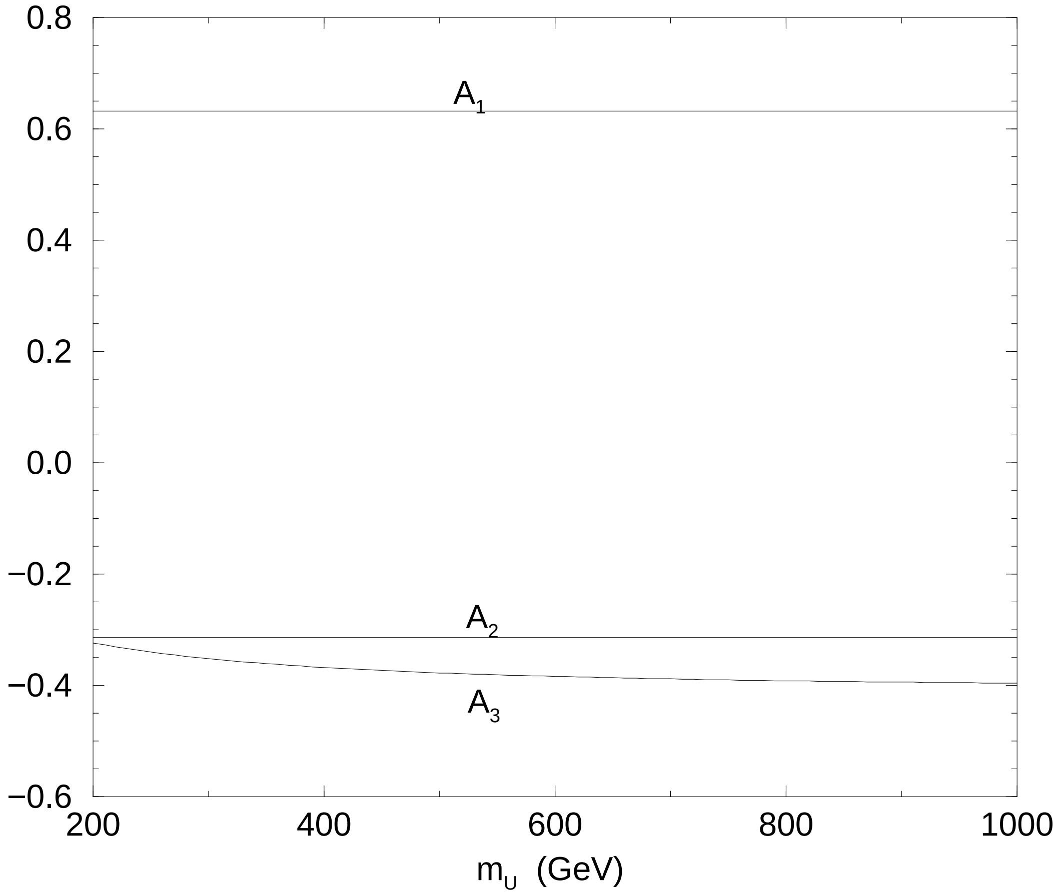

Figure 2: The values of A_1, A_2, and A_3 in Eq. (21).

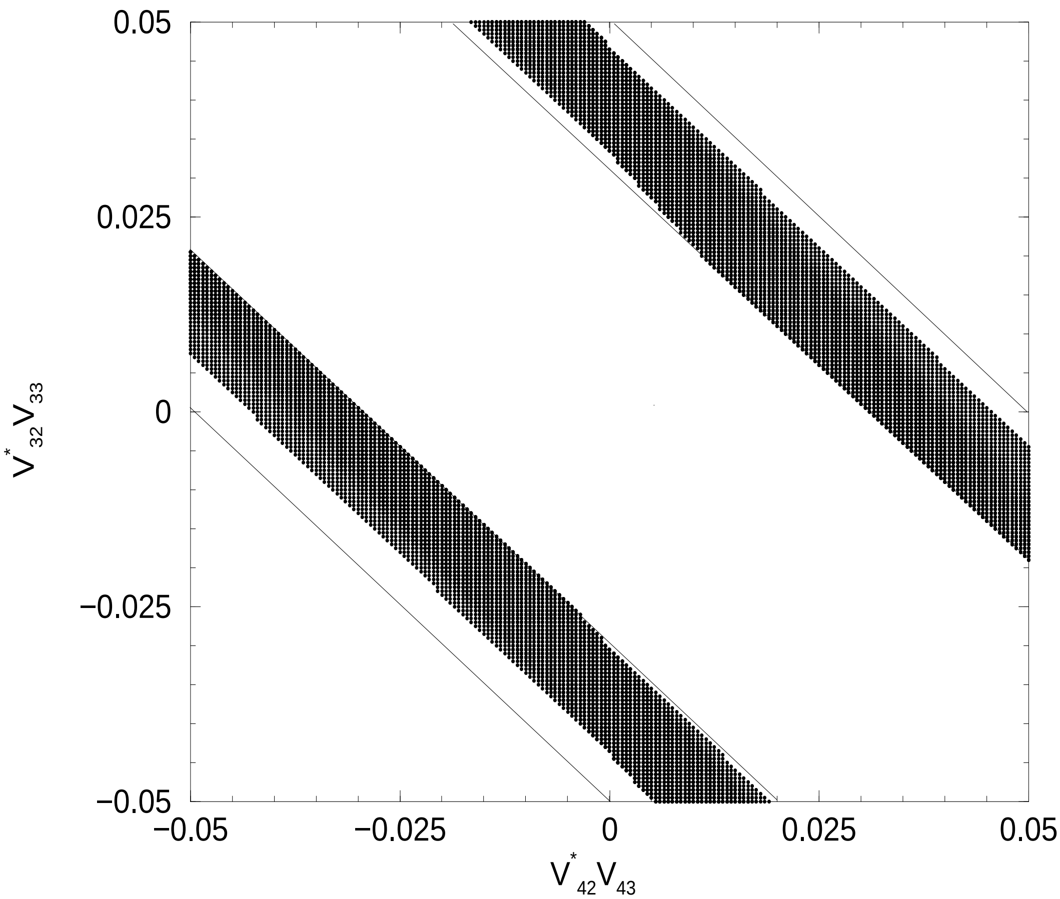

Figure 3: The allowed regions for $V_{32}^*V_{33}$ and $V_{42}^*V_{43}$. $(V^\dagger V)_{23} = 8.1 \times 10^{-4}$.

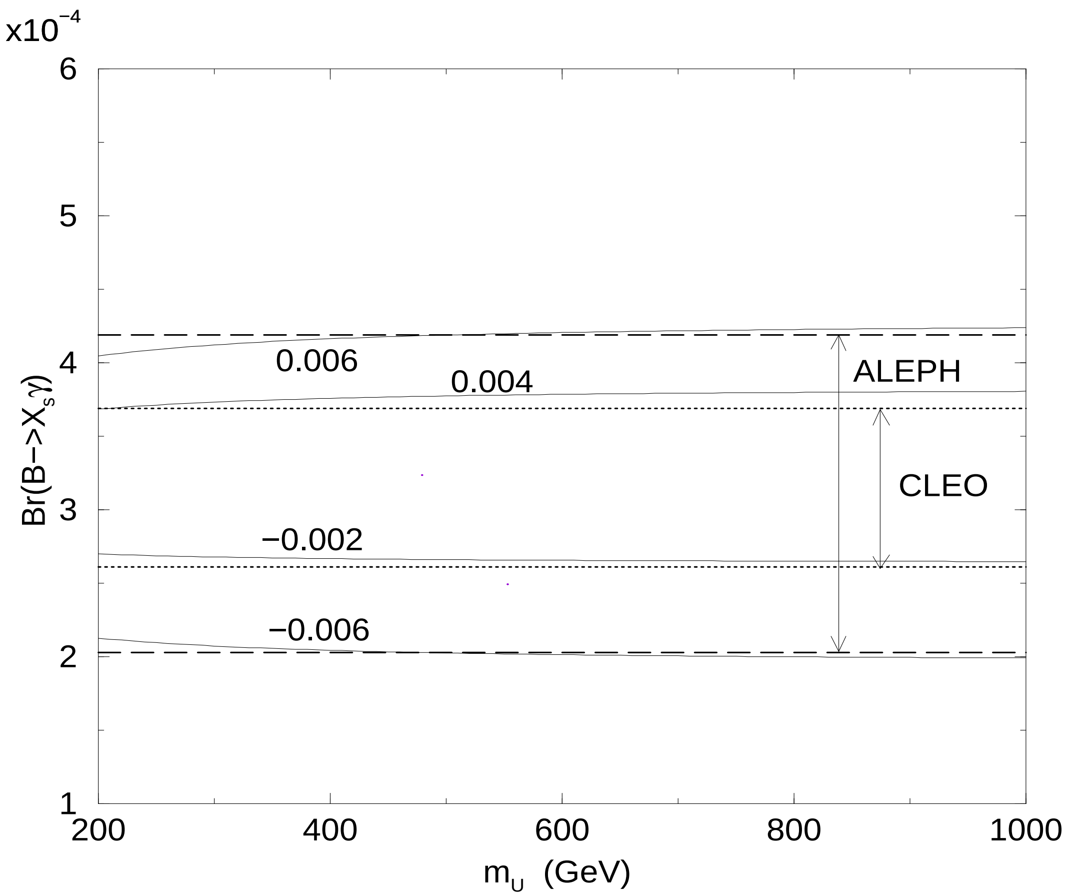

Figure 4: The branching ratio of $B \to X_s\gamma$. $V_{42}^*V_{43} = -0.006, -0.002, 0.004, 0.006$, $V_{32}^*V_{33} = 0.04$, $(V^\dagger V)_{23} = 8.1 \times 10^{-4}$.